8-2015

The cold driver: Driving performance under thermal stress

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Recommended Citation

Morris, Drew, "The cold driver: Driving performance under thermal stress" (2015). *All Theses*. 2236.
https://tigerprints.clemson.edu/all_theses/2236

THE COLD DRIVER: DRIVING PERFORMANCE UNDER THERMAL STRESS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Psychology

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by
Drew Michael Morris
August 2015

Accepted by:
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Abstract

Exposure to cold environments can impact complex task performance and increase cognitive and physiological error in response to thermal stress. Critically, the task of driving a vehicle requires the use of calibrated mental and physical actions to be conducted safely without error. Few studies have examined the effects of cold stress on driving performance and none have explored the potential for advanced driver safety systems to detect error. Active vehicle safety systems which monitor dangerous driving behavior due to drowsiness have been researched and developed, though technology associated with thermal stressed driving error is unexplored. The current study examined the effects of cold stress by way of skin cooling on driving simulator performance and evaluated vehicle behavior metrics for possible dangerous driving detection systems by analyzing behaviors. The presence of lateral lane position variability and velocity variability are of particular interest when speculating detection technology in literature. Forty-four healthy young adults (20 males and 24 females, age 19.97 ± 2.98 years, 4.06 years of driving experience) participated in either a thermal neutral or cooled condition. Cold stress was indexed using skin temperature, core temperature, and subjective cold perception. Participants drove through a simulated track which incorporated vehicle following, stop signs, and curved sections of road. Additional tasks incorporating dexterity and psychomotor vigilance were also used to account for physical and cognitive decrements. The results of the current study found that while the skin cooling methodology was effective in eliciting a behavioral response to the cold, physiological decrements were not observed in the cold condition. Skin temperatures from multiple locations and subjective comfort were significantly lower in the cold condition while core temperature, arm dexterity, and psychomotor vigilance were unaffected. Results from the driving simulator found no difference in lateral lane deviation or vehicle velocity across the track, suggesting traditional drowsy driving detection technology based on these metrics may not be feasible. However, the simulator task did show that participants who had higher subjective ratings of cold followed lead vehicles closer and started to brake later. Participants in the cold condition followed the lead car 22% (0.82 seconds) closer and started braking 20% (2.35 seconds) later when presented with a stop sign during the following task. The current results suggest that drivers exposed to cold environmental conditions are more likely to display aggressive driving behavior.

Acknowledgements

Thank you, the reader, for reading this. Additionally, special thanks is given to Sarah Limyansky, Nicole Horth, and Elizabeth Ferguson for all their help during this project. As well as to my wonderful advisor, June Pilcher.

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Introduction

The Cold Driver: Driving Performance under Thermal Stress

Due to the dangerous nature of impaired driving, factors that may curtail the ability to drive safely should be explored. Healthy humans require thermal stability and comfort to perform optimally. Accordingly, physical and cognitive performance can suffer on account of thermal stress. The task of driving a vehicle requires the use of calibrated mental and physical actions to be conducted safely. Performing complex tasks under cold stress is shown to result in increased error which may reflect the dangers associated with cold environment driving. Furthermore, driving tasks require low physical activity, maintaining attention, and fine tuning movements – elements most susceptible to cooling (Mäkinen, 2006).

Most Americans use a personal vehicle to travel daily, and the majority of these drivers live in regions that experience uncomfortably cold temperatures during several months of the year. Despite this, few studies have looked at the impact of thermal stress on driving performance and the author is unaware of any research associated with cold stress impaired driving detection technology. Modern day detection technology associated with drowsy driving behaviors has been heavily researched and developed, and is growing in popularity due its potential as an advanced safety system to reduce traffic accidents. Drowsy driving detection technology has been shown to reduce driving error and accidents in simulated studies by monitoring vehicle behavior metrics (McCall & Trivedi, 2006). These same metrics may be used for the detection of impaired driving due to cold stress and should also be investigated. The practical relevance of thermal stress research in transportation safety in a similar capacity is indisputable, and such research would provide a scientific foundation for future driving stress studies.

Thermal Comfort and Driver Performance

Thermal comfort is critical to human performance and is commonly assessed as a subjective measure of temperature perception on a seven item scale; referred to as a thermal comfort assessment (TCA) (Brooks & Parsons, 1999; Cengiz & Babalik, 2007; Parsons, 2002). Due to the nature of environmental stressors, discomforting thermal stress can occur anywhere air temperature fluctuates and has been shown to vary excessively in vehicle cabins (Grundstein, Meentemeyer, & Dowd, 2009). A vehicle cabin thermal comfort can be exceptionally challenging to maintain because it is an asymmetrical thermal environment with temperature variations throughout the cabin (Brooks & Parsons, 1999). The interior thermal fluctuation results from radiating environmental temperature outside of the cabin, either hot or cold. Such temperature fluctuation due to an environmental source has been shown to correlate with traffic accidents. Cross-sectional analyses of motor vehicle incidence in the United States assessed ten potential factors that influence traffic accidents and found that temperature was the third leading factor of accidents, more so than even alcohol abuse (Zlatoper, 1991). The advent of advanced climate control systems in vehicles helps mitigate the severity of thermal stress, but cold stress still remains a constant element in cooler environments prior to vehicle heating (Farzaneh & Tootoonchi, 2008).

Presently, the scientific literature on driving performance under cold stress is limited. A single laboratory study by (Daanen, van de Vliert, & Huang, 2003) found that cold stress resulted in significantly increased error in driving performance on a low fidelity simulator when measuring for lane-keeping ability. The study demonstrated that temperatures of 41°F for thirty minutes were sufficient to cool mean skin temperature of drivers without any drop in core temperature, and result in impaired driving. The researchers posited that the combination of psychological and physiological factors attributed to the performance decrement. Additionally, a limited number of thermal stress studies have shown the detrimental effects of temperature on real road driving. Researchers found that drivers missed 50% more visual signals while under mild thermal stress when operating a vehicle and were significantly more likely to lose their sense of direction during five hours of real road driving (Norin & Wyon, 1992).

Because applied research in driving performance under thermal stress is limited, research in complimentary disciplines such as psychology and physiology may be used to supplement our lack of performance observations. Few thermal studies have used a complex driving performance task, however literature is rich with studies that have explored the effects of cold stress on simple tasks which make up the elements of vehicle operation.

Cold Stress and Cognitive Performance

Studies and reviews have shown the effects of thermal stress on cognitive performance across a variety of tasks. Temperature has a negative impact on cognitive performance because of the body's response to this stress. It can be assumed then that tasks requiring cognitive performance may be curtailed by cold stress. Paradigms attempting to best explain the relationship between cognitive performance and thermal stress have been proposed throughout the years. Perhaps the most prominent and applicable of these is the Yerkes and Dodson inverted-U theory, discussed at length in a meta-analytic review (Hancock, Ross, & Szalma, 2007), suggesting that increased stress is met with decreased human performance.

Researchers have expanded on this theory with their own extended-U model, focusing on attentional resource capacity and its homeostatic nature until a threshold of stress is crossed (Hancock & Warm, 1989).

Temperature prior to and during the task is often the primary manipulation in cold stress research. Importantly, these prior temperatures are known to influence the perception of later temperature due to the rapid adaptability of thermoreceptors (Parsons, 2002). Accordingly, temperatures may feel colder than they really are because of recent exposures to less cold environments. Looking at the effect of cold exposure intensity, temperatures below thermal neutral (i.e., cold) have been correlated with generally reduced cognitive performance. Meta-analytic findings have shown that participants performing tasks in a cold condition (50-64.9°F) had a 7.81% decrement in cognitive performance, while participants in colder conditions (<50°F) had an even worse 13.91% decrement in cognitive performance – as compared to a thermal neutral condition (65-75°F) (Pilcher, Nadler, & Busch, 2002).

When reviewing the length of cold stress exposure, Pilcher et al. (2002) states that cold exposure of less than one hour had a greater negative impact on cognitive performance than exposure of more than one hour. This impact is perhaps due to the aforementioned effects of prior temperature exposure. As such, poor cognitive performance can be problematic for vehicle operation. An interior vehicle heating system requires time to warm up and thoroughly heat the driver’s environment in cold conditions. Vehicle heating systems are dependent on outdoor temperature intensity and volume of interior space when heating, and may expose the driver to cold stress for long periods of time. It has been speculated that cognitive decline in these cold environments might be less impacted following long term repeated cold exposure, but an increase in mental performance due to physiological adaptation is unlikely (Mäkinen et al., 2006). Participants involved in a ten day repeated exposure study at 50°F did not show significant improvement on cognitive tasks over time when compared to a control group. Instead, long exposure still resulted in increased response time, decreased accuracy, and decreased efficiently; components vital to proactive and safe driving.

The impact of thermal stress on cognitive performance also depends on the task being performed. When analyzing task performance by categories, Pilcher et al. (2002) found that tasks based on reasoning, learning, or memory saw a severe 28.05% decrement in performance during cold exposure, and a moderate 7.81% decrement in attentional and perceptual tasks. However, other reviews of thermal stress and cognitive performance have found that cold stress has the largest impacts on perceptual based tasks and psychomotor performance (Hancock et al., 2007). Within reaction time performance there is some disparity as to the effect size during thermal stress, though agreement that the effect is present (Hancock et al., 2007; Pilcher et al., 2002). Measures of reaction time as well as attention have been reliably measured using button based psychomotor vigilance tasks (PVT), but additional research is needed to further understand the relationship between cold stress and reaction time as it pertains to vehicle operation (Jung, Ronda, Czeisler, & Wright, 2011). Despite some need for further research, literary reviews have consistently found that the vital cognitive components involved in safe driving are impacted by cold stress. Indeed, (Jackson, Croft, Kennedy, Owens, & Howard, 2013) demonstrated that driving is a complex cognitive task that involves attention, perception, working memory, and psychomotor vigilance.

Loss of attention due to extraneous distractions is often cited as the primary reason for poor cognitive performance during cold stress. Researchers have found that skin temperature cooling impaired attention by acting as a distractor, but cooling core body temperature did not further impair cognitive performance (Cheung, Westwood, & Knox, 2007). Additionally, research has shown that engaging in exercise to increase body core temperature during cold stress did not improve attention while the participants were subjected to a cold environment, once again due to distraction (Muller et al., 2011). The researchers postulated that this finding is evidenced by the arousal and distraction theories for simple attention. This gives support to the theory that cold environments impact cognitive performance through simple skin temperature cooling independent of core temperature. An extensive report sponsored by the Department of Transportation identified distracted driving as one of the leading causes of automobile accidents today, accounting for over one-million accidents a year (Royal, 2003). In this report, 23% of accidents caused by distraction were not attributed to any of the previously defined categories (e.g., using technology, passengers, looking for street signs, etc.), and may be partially attributed to the thermal stress of vehicle interior temperature. Additionally, the cold could have contributed to inattention, a result of limited attentional resources shown to reduce driver response performance (Yanko & Spalek, 2014). Despite plausibility, extensive meta-analytic reviews have not addressed the topic of thermal stress when considering attentional performance and driving, which suggests a necessity for additional research (Langner & Eickhoff, 2013).

In addition to the distracting temperature theory, the arousal paradigm also helps explain the cognitive impact of cold stress. Cold environments introduce a temporary arousal response from stress, limiting cognitive performance and accuracy (Hancock, 1986). Indeed, previous driving simulator research has shown that physiological arousal plays a role in driving behavior, and stress resulted in drivers feeling less comfortable with their driving ability (Schmidt-Daffy, 2013). Researchers found that arousal due to thermal stress attributed to performance decrease on a complex driving task involving signal detection (Wyon, Wyon, & Norin, 1996). Another study found that cold air was enough to induce adrenergic stress in a command and control task (Benoit, van Orden, & Osga, 1996). The result of this arousal suggested a speed-accuracy tradeoff, whereby reaction time improves but error rate increases in response to the stress of cooled skin (Enander, 1987).

Cold Stress and Physical Performance

As with cognitive performance, physical performance is affected by thermal stress and is a crucial component of driving performance. Physical performance decrement may be a direct result of the cold (e.g., frostbite), or a self-induced result of the body's defensive reaction to the cold (e.g., shivering, stiffness, and numbness). Although hypothermia from lowered core temperature is often associated with poor performance, performance decrement often occurs as a result of simple skin temperature cooling.

Cold-induced vasoconstriction and vasodilation (CIVC and CIVD) is the body's common defensive reaction to cold stress, and contributes to decreased physical performance. In CIVC, the muscular walls of the peripheral arteries and arterioles constrict to keep warm blood distant from the epidermis and to prevent net heat loss through radiation. As CIVC pulls blood away from the surface of the skin, the reduced blood flow puts the skin in danger of dermal freezing damage (e.g., frostbite). In order to prevent dermal damage, the body next engages in reoccurring cycles of dilation to increase blood flow again. This event is often referred to as the *hunting phenomenon* (Parsons, 2002). Studies have explored the role of acclimatization in the onset CIVC and found that habitual exposure to cold can encourage increased blood flow to the extremities earlier if done periodically for several months or more (Mekjavic, Dobnikar, Kounalakis, Musizzar, & Cheung, 2008; Rintamaki et al., 1993).

This narrowing of the blood vessels is most commonly noticed in the distal appendages (e.g., hand and feet), which lose manual dexterity and become hypoesthetic (i.e., lose touch sensitivity) from a reduced blood supply and non-shivering tonus. The result of CIVC is increased error on tasks that require accurate motor control and detriments in reaction, sensitivity, nerve conduction, grip strength, time to exhaustion and dexterity (Ducharme, Brajkovic, & Frim, 1999; Heus, Daanen, & Havenith, 1995). Research has shown that cooled skin temperature also impaired performance and control on hand tracking tasks involving arm movement, which showed an increased error rate following cooling (Goonetilleke & Hoffmann, 2009). As dexterity loss impacts driving performance, this increase in arm movement error may potentially translate to increased error in steering wheel and foot pedal control. Importantly, they also found that loss of dexterity became more profound with increased cold stress intensity.

Another important physiological response to cold stress that may inhibit safe driving performance is shivering thermogenesis. Researchers noted that shivering due to cold stress may hinder driving performance in simple driving tasks (Daanen et al., 2003). Shivering has also been shown to cause decreased performance in tasks requiring fine motor control by introducing muscular perturbations (Meigal, Oksa, Hohtola, Lupandin, & Rintamäki, 1998). This was especially true for larger muscle groups, such as the shoulder, which struggled to accurately apply a sustained amount of force during shivering. Similar to the issues associated with dexterity loss, lack of muscular control may potentially translate to increased error in steering wheel control or foot pedal control by introducing variability. Importantly, research by (Imbeault, Mantha, & Haman, 2013) demonstrated that this detrimental shivering can occur from simple skin cooling due to short-term thermal stressors. A short-term thermal stressor easily obtainable in vehicle cabins.

Several measures serve as indices of dexterity loss due to cold exposure. The Purdue Pegboard Task is perhaps the most common measure, but does not account for loss of dexterity in larger muscle groups which affects vehicle control (Ducharme et al., 1999). More appropriately then, the Minnesota Manual Dexterity Task (MMDT) focuses on large muscle group dexterity in the upper body, and has been shown to correlate with performance on the Purdue Pegboard Task (Desrosiers, Rochette, Hébert, & Bravo, 1997).

Dangerous Driving Detection Technology

The potential for technology to inform a driver of their impairment is of great benefit to transportation safety and advanced driver assistance systems (ADAS) development (Werneke, Kleen, & Vollrath, 2014). Stress causes dangerous driving, and current automotive research has shown that driver impairment often result in systematic and predictable variability that can be used as an indicator of this dangerous driving. Currently, ADAS such as drowsy driving monitoring systems are available in modern vehicles, and detect driver impairment due to drowsiness.

Though the development of this technology is ongoing, there have been two distinct methods of approaching the problem of dangerous driving detection due to drowsiness. The more invasive of the two is the *operator behavior* approach using biometric indicators. Using this method, an intelligent system monitors the behavior of the driver directly without any input from the vehicle. These direct measures include monitoring the driver’s eyes (PERCLOS) or using electroencephalogram (EEG) to monitor brain activity, both of which are indicative of a driver entering early stages of sleep (Kecklund & Åkerstedt, 1993; Sandberg et al., 2011b). In addition, other systems have used various combinations of electromyogram (EMG) to monitor loss of muscle tonus or atypical muscle movements associated with vehicle correction, another indicator of sleep onset (Lal & Craig, 2001). However, biometric measures in a natural setting can be intrusive and unreliable (Shuyan & Gangtie, 2009).

The second and more applicable of the two methods of detecting dangerous driving is the *vehicle behavior* approach using vehicle indicators. Using this method, an intelligent system monitors the driver indirectly using input from the vehicle’s behavior. These measures include monitoring the relative location and variability of a vehicle within the lane, as well as instances when the vehicle leaves the lane altogether (Forsman, Vila, Short, Mott, & Van Dongen, 2013; Sandberg, Åkerstedt, Anund, Kecklund, & Wahde, 2011a). Additional measures include monitoring for atypical steering wheel movements or accelerator and brake pedal forces (Liu, Hosking, & Lenné, 2009). Unlike the biometric based method, monitoring the vehicle behavior may be directly applicable to cold stress driving impairment. Vehicle behavioral metrics are not concerned with the reason for the impairment, only that the vehicle is behaving in a dangerous manner that is correlated with an impaired driver.

In drowsy driving, cognitive and physical decline results in systematic driving error following sleep deprivation. The application of the current drowsy driving detection technology to thermal stress research is dependent on driving behavior under cold stress being similar to driving behavior while drowsy. As has been shown, cold stress impacts performance on cognitive tasks by impairing perception, reasoning, learning and reaction. Cognitive performance decline is also critically linked to attentional deficit due to the distracting effects of cool skin temperature (Cheung et al., 2007). Additionally, cold stress impacts performance on physical tasks by impairing haptic sensitivity, manual dexterity, and fine motor control. By comparison, sleep deprivation has also been shown to impact performance on cognitive tasks by impairing perception, reasoning, learning and memory (Goel, Basner, Rao, & Dinges, 2013). Drowsiness has also been strongly linked to attentional deficit similar to cold stress (Langner & Eickhoff, 2013; Roca et al., 2012). Sleep deprivation can also impact performance on physical tasks by impairing manual dexterity, and fine motor control (Eastridge et al., 2003).

Because of the significant overlap in task performance decrement between drowsiness and cold stress, cold drivers may demonstrate the same systematic errors. Standard deviation of lateral lane position has long been held as one of the most popular and reliable measurements of drowsy driving detection, indexing dangerous driving through vehicle behavior. A single study on the topic by (Daanen et al., 2003) found this overlap, showing that cold stress can result in significantly increased driving performance error on a low fidelity simulator when measuring lateral lane position.

Cooling Methodology

Because skin temperature can trigger a cognitive and physiological response to thermal stress, techniques have been developed to artificially manipulate the perception of environmental temperature. One technique is through the use of cooling vests, showing that a heat sinking vest with a phase-change material (e.g., ice) worn over basic clothing can lower torso skin temperature as well as mean skin temperature without significantly affecting core temperature (Yifen, Nan, Wei, Guangwei, & Baoliang, 2011). Other researchers have also found that an ice jacket significantly cooled torso skin temperature and additionally added thermal discomfort (Duffield, Dawson, Bishop, Fitzsimons, & Lawrence, 2003). Again, no significant difference in core temperature was found when using the apparatus to encourage cold stress.

Climate chambers have also been utilized in several cold stress studies. Climate chambers are insulated independent rooms dedicated to environmental conditions research and are the closest facsimile to naturally occurring environments (Spitznagel et al., 2009). Unlike some methodologies, they offer a symmetrical thermal stressor that cools the entire body evenly using heated or cooled air. However, use of such equipment is often limited by the funds require to operate the chamber.

Purpose and Hypotheses

Hypothesis 1: The impact of cold stress from cold environments on human performance is well documented. Skin cooling has been shown to be an effective method of introducing cold stress without subjecting participants to hypothermic states. Studies have shown that skin cooling can be achieved using a cooling vest placed over participants clothing. This study expects to see a measurable level of cold stress in the Cold condition. The Cold condition is expected to result in *1a)* increased subjective ratings of thermal discomfort, *1b)* increased cold perception on a TCA questionnaire compared to the Thermal Neutral condition, *1c)* and a decrease in skin temperature while core temperature remains constant.

Hypothesis 2: There is very little research on the impact of cold stress on driving performance, but evidence that cold stress impacts the individual performance components of driving performance is discernible. Previous research has shown that cooled skin temperature results in poorer cognitive performance during high cold stress from limited attention resources and accuracy tradeoffs from hyperarousal, hindering performance on related tasks. This study does not expect to see a decrease in cognitive performance during cold stress, because of the mild cooling method used. *2a)* The Cold condition group is not expected to show poorer attentional performance as denoted by an increase in missed responses on a PVT task, *2b)* The Cold condition group is also not expected to show a decrease in reaction time *2c)* or an increase in false starts on a PVT task compared to the Thermal Neutral condition.

Hypothesis 3: Physical ability can be impacted by cold stress and is another important component of driving performance. Research has shown that extreme skin cooling can induce shivering in large muscle groups and limit blood flow to the extremities, which affects dexterity by limiting motor control through the introduction of muscular perturbations and the reduction of blood supply. This study does not expects to see a decrease in physical performance due to cold stress, because of the mild cooling used. The Cold condition is not expected to induce shivering thermogenesis which would limit performance on a MMDT arm dexterity task. As such, completion compared to the Thermal Neutral condition should be similar.

Hypothesis 4: Research has shown that stressors have a detrimental impact on driving performance, as is shown by an increase in driving errors and limited lane keeping ability in simulated studies. Research has also shown the detrimental effects of mild cold stress on cognitive and physical performance overlaps with that of other stressors. The cognitive and physical toll of cold stress is expected to result in poor driving performance as measured through traditional safe driving detection measures and a car following task. Following a statistical analysis, the Cold condition group is expected to impact driving performance through increased variability in *4a)* lateral lane vehicle movement, *4b)* vehicle velocity, *4c)* and following distance.

Methods

Participants

Fifty students were admitted into the study, due to simulator sickness during the session 6 did not continue to the end of the driving task and their data were not used. Forty-four students (24 females and 20 males) with an average age of 19.97 years (standard deviation = 2.98) and who met the criteria completed the study. Neither group (group 1, age 19.34 ± 1.13 years, 12 females and 10 males; group 2, age 20.61 ± 4.02 years, 12 females and 10 males) varied on any significant demographics in this two group between subjects design.

Participants were recruited from undergraduate psychology courses at Clemson University using the SONA System Human Subject Pool Management Software. Participants who completed the study were awarded research participation credit in their class as well as $10 monetary compensation. If a participant chose to leave the study before the completion of the testing, they were still awarded participation credit and monetary compensation. Individuals interested in participating in the study registered using the SONA System and then completed a general information questionnaire (see Appendix **[1]**). In this questionnaire, each participant was briefly surveyed for medical and personal information relevant to the study prior to laboratory testing. Criteria for data inclusion included the volunteer's status as a Clemson University student, the possession of a valid driver's license, a non-drug or excessive alcohol user, a non-smoker, in good health, a proficient English speaker, and no diagnosed history of sleeping disorders. Participants were also required to be between the ages of 18-38 to participate. Participants completed a scheduling form to determine which dates they were available for testing (see Appendix **[2]**).

Setting and Apparatus

The study was conducted in an 880 square foot room in Brackett Hall on Clemson University's main campus. The room contained a projection-based driving simulator, as well as all tasks and equipment required for the practice and testing sessions (Figure 1). The room was controlled and monitored for temperature and humidity.

Figure 1. The room used during data collection with driving simulator pictured in the middle.

Materials and Equipment

PVT Unit

Participants performed a reaction task using a computerized Psychomotor Vigilance Testing program (Khitrov et al., 2014) as a control measure for psychomotor decrement. The participants were told to press a response button as soon as the device visually prompted them, whereby the program logged the delay in the participant's response in milliseconds. The time elapse data were used to record differences in reaction times between conditions. Users were prompted randomly after a 2 to 10 second pause between trials, the task took 5 minutes to complete in total. The participants were given a training session to become familiar with the device by completing a shortened 1-minute session of the typical task.

In addition, participants performed an attention task using the same program. Similarly, the participants were told to press a response button as soon as the device visually prompted them, whereby the program logged the delay in the participant's response in milliseconds. The time elapse data were used to record differences in sustained attention between conditions when there was a delay in response >500 & >1000 milliseconds (i.e., response lapse). Users were prompted randomly after an extended 45 to 60 second pause between trials, the task took 10 minutes to complete in total. The participants were given a training session to become familiar with the device and the extended pause time by completing a shortened 1-minute session of the typical task.

Minnesota Manual Dexterity Task

Participants performed a hand-eye dexterity test using the Minnesota Manual Dexterity Placing Task (MMDT, Lafayette Instruments) as a control measure for physical decrement (Figure 2). Participants were told to sit at a table and place sixty circular disks into sixty circular holes as quickly as possible using only one hand. The task has been shown to reliably measure an individual's rapid eye-hand coordination and dexterity. The task took approximately 1 minute to complete each trial, and four trials were completed in total. The participants were given a training session to become familiar with the device by completing a 2-minute walkthrough of the task. The time required to complete the task was used to record loss of dexterity due to cold stress.

Figure 2. The Minnesota Manual Dexterity Placing Task

Cooling Vest

An adjustable nylon vest with large plastic packs filled with a phase-change material (FlexiFreeze, Mequon, WI) was used as the cold stressor during the cold conditions (Figure 3). The phase-change material was a freezable liquid that acted as a heat sink to remove heat from the surface of the participant's anatomical trunk. The packs of liquid were removed from the vest once melted and refrozen in a refrigeration unit before future use. An additional cooling pack was placed on the seat of the driving simulator, as well as on the seat at that table where the additional dexterity and psychomotor tasks were completed.

Figure 3. Cooling vest

Tympanic and Oral Thermometers

Internal body temperature was estimated using both an infrared tympanic thermometer as well as an oral thermometer (Figure 4). A Thermoscan 5 ear thermometer (Braun; Kronberg, Germany) was placed in the participant’s ear and used to record the temperature of the tympanic membrane. The instrument was placed against the participants left ear for five seconds and was protected using a sanitary lens cover. Additionally, a digital probe thermometer (Omron; Kyoto, Japan) was placed under the participants tongue with their mouth closed for 20 seconds and used to record the temperature near the lingual artery. Temperatures from both methods were reported as estimates of internal body temperature.

Figure 4. Infrared tympanic thermometer

Thermocouple Data Logger

Skin temperature was estimated using a portable four-channel real-time data logger with insulated thermocouples from four body locations (Figure 5). An Omega RDXL-4SD data logger (Omega Engineering; Stamford, CT) logged skin mean temperature at 0.1 Hz using Type K chromel-alumel thermocouples from four locations. Thermocouples were placed on the right abdominal, the right lower back, the back of right thigh, as well as the front of right thigh. A second female researcher was present and applied the thermocouples when a female participant was there. Thermocouples were secured to the participants using breathable medical tape. The thermocouples remained on the participant throughout the entirety of a laboratory testing session.

Figure 5. Skin temperature data logger

Qualitative Measures

Three qualitative questionnaires were used throughout the study. Participants reported subjective feeling of sleepiness using the Stanford Sleepiness Scale (SSS) (Hoddes, Dement, &

Zarcone, 1971). Feelings of sleepiness from circadian rhythms or sleep deprivation can impact driving performance as well as cognitive performance and were monitored to control for variability. The Likert scale ranged from 1, in which the participant was feeling active, vital, alert, and wide awake; to 7, in which the participant was no longer fighting sleep, the sleep onset was likely to occur soon, and was having dream-like thoughts (see Appendix **[5]**).

Participants reported subjective feeling of sickness using the Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Berbaum, & Lilienthal, 1993). Feelings of sickness from the driving simulator can impact driving performance as well as cognitive performance by inducing discomfort and were monitored to control for variability. The questionnaire asked sixteen questions pertaining to feelings of fatigue and discomfort associated with simulated environment sickness. Each question was answered using a Likert scale ranging from None, having no symptoms pertaining to that question; to Severe, having severe symptoms pertaining to that question (see Appendix **[9]**).

Participants reported subjective feeling of thermal sensation and discomfort using the Thermal Comfort Assessment (TCA) (Parsons, 2002). The questionnaire asked four questions pertaining to feelings of being too hot or too cold. The first question was answered using a Likert scale ranging from 1, feeling very hot; to 9, feeling very cold; with 5 representing neutrality. The second question was answered using a Likert scale ranging from 1, feeling very comfortable; to 5, feeling very uncomfortable. The final two questions were answered using simple yes or no, and asked whether there were visible signs of shivering or sweating (see Appendix **[8]**).

Driving Simulator

Participants performed a driving task in a driving simulator. The task required drivers to keep to their lane, stop at multiple intersections, and follow a lead vehicle. The DriveSafety RS 600 driving simulator (DriveSafety Inc.; Murray, UT) was a high fidelity system integrated into a fully functioning Ford Focus cab on a pitch and longitudinal mobile base. The cab had fully functioning controls and steering wheel force feedback. The simulator was additionally equipped with a fan in the driver's side footwell and a fan which blew across the cab to encouraged cold stress in the Cold condition using wind chill similar to a typical vehicle climate control system. Using the DriveSafety HyperDrive Authoring Suite software, a five channel projection system displayed a 300° (five screens at 60°) horizontal field of view environment at 60 frames per second. For both conditions the simulated environment depicted a high visibility daytime driving scenario through 14 miles of rural roads with straights, curves and sloped segments. In total, the participants took approximately 12 minutes to complete the full circuit with a speed limit of 55 miles per hour (Figure 6). The participants were given a 3-minute training session to become familiar with the simulator by completing a shortened version of various road segments found in the testing circuit. During the following portion of the task, the participants were required to follow another vehicle that was driving 10mph under the 55mph speed limit. After approximately two minutes of following, that vehicle would eventually run through a stop sign and exit off the road. No other vehicles were present during either the training or the testing session other than during the brief following task. Participants were told to drive as they normally would and obey all traffic signage and laws. The driving simulator continuously recorded several vehicle behavioral metrics at 5 Hz throughout the testing session.

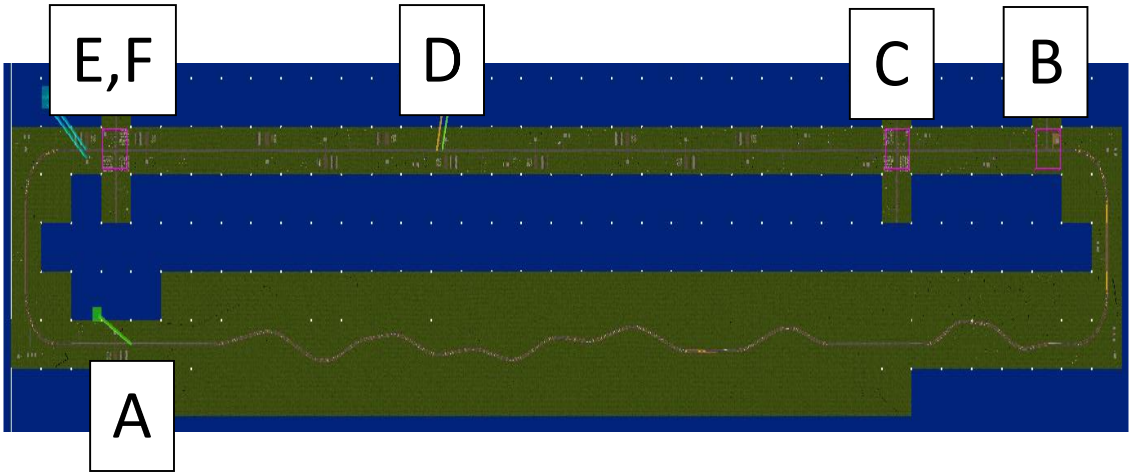

Figure 6. The overhead view of the track used in the driving task. A) Start and finish location B) Intersection/stop sign 1 C) Intersection/stop sign 2 D) Start of following task E) End of following task F) Intersection/stop sign 3.

Design

Conditions

The study used a between-subjects design with two conditions. The first of the two conditions was a Thermal Neutral condition, in which the participant performed the tasks wearing a non-cooled version of the cooling vest with room temperature cooling packs in a calm air environment. In the second condition, Cold, participants performed the tasks wearing a cooled version of the cooling vest with frozen cooling packs in a moving air environment to add a wind chill factor. In the vehicle two fans provided the wind chill, out of the vehicle a single fan next to the testing station provided the wind chill. The participants were randomly assigned to only one of the two conditions.

Condition Design

In each testing condition the participant underwent a driving task followed by two short qualitative questionnaires to assess the participant's feelings of simulator sickness and perceived thermal comfort. At this time, the participants' internal body temperature was also recorded from the ear and mouth. Next participants completed three additional tasks (two psychomotor vigilance measures and one physical performance measure) in a randomized order. The thermal comfort questionnaire and internal body temperature readings were administered after each of these tasks. This concluded the study. Skin temperature was logged continuously throughout the training and testing sessions.

Reliability Measures

Research staff members, both undergraduate and graduate, were fully trained in study procedure prior to participant testing. All study procedure descriptions were written out prior to testing to ensure each participant received the same instruction and information (see Appendix **[7]**). A researcher monitored participants throughout the testing sessions and recorded any problems that occurred for the purpose of data integrity (see Appendix **[6]**). Task performance and temperatures were recorded by the researcher immediately following each administration (see Appendix **[4]**).

Procedure

This study was approved by the Institutional Review board of Clemson University prior to any data collection. Participants involved in the study read over the study description and were given the opportunity to ask questions before signing the informed consent form. All procedures took place during one testing session.

Individuals who expressed interest in participating by signing up through SONA were sent a study description as well as a general information questionnaire prior to their commitment (see Appendix **[1]**). Participants were then sent a scheduling form to identify their availability to report to the laboratory for a single one-hour testing session if there was a conflict with the SONA time (see Appendix **[2]**). This form included further instruction on how to prepare prior to the session. Participants admitted into the study were told to sleep eight hours on the night before the session, and to wake at least two hours before their scheduled time on the day of the session. On the day they were scheduled to report to the laboratory participants were told to refrain from consuming any energy supplement products, caffeine or alcohol. In addition, participants were told to arrive at the lab with clothing that would offer 0.24 Clo (standard unit of clothing insulation) of clothing insulation – underwear, athletic shorts, a cotton t-shirt, and gym shoes with low socks.

Participants reported to the lab at a prearranged time. Once they arrived, participants were given the chance to have questions answered before they signed the informed consent and began any procedures. Once signed, information on basic biometrics was taken and the thermocouples used for the skin temperature measures were attached (see Appendix **[3]**). The basic biometrics included height in inches, weight in pounds, internal body temperature from the ear and mouth, and body fat percentage estimated through a four point-of-contact bioimpedance scale. Temperature thermocouples were attached to the participant’s lower abdomen, lower back, front of thigh, and back of thigh using breathable medical tape, and were connected to a portable data logger. Participants then filled out the section of the form which assessed sleep habits and their rating on several qualitative scales including sleepiness, thermal comfort, and simulator sickness symptoms (see Appendix **[3]**).

Before any testing occurred, participants underwent a truncated training session with each task and measurement and did not start the testing session until they felt comfortable with the procedures involved. Participants were considered comfortable with the task when they confirmed they had no questions pertaining to the correct completion of the task or operation of the apparatus. This included driving a 3-minute training track with the driving simulator, a 1-minute session with the reaction time PVT, a 1-minute session with the response lapse PVT, and a 2-minute slow walkthrough session of the MMDT.

Once training was complete, the participants then started their randomly assigned condition. Before the driving task, the participants put on the corresponding vest (cooled or non-cooled) and had researchers adjust it to fit snug. In the Thermal Neutral condition, participants sat in the driver's side of the simulator with a large room temperature cooling pack on the seat bottom. The first part of the task involved driving normally on a winding roads until they were required to stop at an intersection, this lasted approximately 5 minutes. During the second part, participants drove on a straight road and stopped at two four-way stop intersections, this lasted approximately 5 minutes. During the third part, the participant had to follow the car in front of them as they normally would until the car ran a stop sign and turned off the road, this lasted approximately 2 minutes. Participants were not given any information as to the events that would occur on the track, only that they should drive as they normally would, to obey all signage, and to not pass any vehicles if they should be in their lane. Participants were not told how long the simulation would take, though the driving task took approximately 12 minutes to complete. Participants were told to inform the researcher if they were feeling nauseous from the simulator and were informed of the signs of simulator sickness. Following the completion of this task the SSQ and TCA were administered and internal temperature was recorded from the two locations.

After the driving task, participants completed the two PVT tasks and the MMDT in a randomized order. Following the completion of one task, the participants were asked the TCA questions and had their temperature taken, then immediately started the next task. The two psychomotor vigilance tasks and dexterity task were completed while seated in front of a table with the appropriate cooling packs on the seat while wearing the appropriate vest. Following the completion of the three additional tasks, the TCA was again administered to qualitatively measure perceived thermal stress and internal temperature was recorded. Once the participants completed this assessment, the study was completed.

With the exception of the cold stressor (i.e., cold cooling vest with moving air) the Cold condition was identical to the Thermal Neutral condition. The moving air that came from a fan inside the simulator pushed room temperature air against the participants' lower body and torso to exacerbate cold perception. Following the completion of the tasks, the participants in the cold condition were placed in front of a heating fan if they were feeling uncomfortably cold.

Safety Measures

All appropriate measures were taken to ensure the cold condition did not put the participant at risk for exceptional discomfort or harm. Levels of cold stress which precipitate health risks due to hypothermia (internal temperature < 95° F) were avoided in this study, as skin cooling occurs independently of core temperature cooling (Daanen et al., 2003; Ducharme et al., 1999; Parsons, 2002). Previous studies have used a frozen cooling vest worn over basic clothing to lower skin temperature, and successfully administered a thermal stress without affecting core temperature (Duffield et al., 2003; Yifen et al., 2011). Additionally, internal temperature was periodically monitored as a proxy measure for core temperature using two methods to ensure the participants safety.

Cold stress impacts task performance partly due to discomfort from skin cooling. Levels of cold stress which instigate pain due to low skin temperature were avoided in this study. The occupational ISO standard for the Ergonomics of the Thermal Environment (ISO 13732) established skin temperature 32° F as the thresholds for freezing damage (Parsons, 2002). Previous studies using a frozen cooling vest for inducing cold stress found a 10° F drop in torso skin temperate compared to a control condition with a non-cooled cooling vest (Yifen et al., 2011). Other studies have found cooling vests to lower torso skin temperatures by as much as 17° F, again resulting in a safe cooled skin temperature (Duffield et al., 2003). In addition, skin temperature was continuously monitored throughout the study using thermocouples at four locations to ensure the participants safety and comfort.

Variable Analysis

Following participant testing, data were organized and analyzed using Microsoft Excel spreadsheets and the IBM SPSS 22 statistical package. The independent variable being manipulated was the participant's level of thermal stress. Cold stress was quantitatively measured using mean skin temperature from four locations, wind chill calculations, and estimated internal temperature from two locations. The dependent variable was the participant's performance on the separate parts of the driving task, performance on the cognitive and physical measures, as well as their response on the qualitative questionnaires. Lane position, vehicle velocity, vehicle following distance, and braking behavior were the driving measures of primary interest.

Data Analysis

PVT

The performance measures for the PVT tasks were the participant's reaction time recorded in milliseconds and the presence of reaction time lapses during the extended pause attention task. The PVT program recorded the participant's response time as soon as the unit displayed a visual signal. Reaction time responses were recorded during a 5-minute task. Reaction time lapses were also recorded during a 10-minute task. Lapses were cases in which the individual's response took longer than 500 milliseconds. Lapses and inverse reaction times were associated with their respective condition and used as a descriptive statistics of cold stress. A two sample t-test was used to assess significant differences in PVT performance between conditions.

Subjective Measures

The performance measure for the SSS was the participant's qualitative sense of sleepiness as indicated on a 7-point Likert scale. Self-perceived sleepiness data were associated with fitness to complete the study. Participants indicating sleepiness scores above a 4 (i.e., feeling foggy) did not participate in the study. No difference in sleepiness scores between groups was observed (cold group, 2.36 SSS score; thermal neutral group, 2.13 SSS score). The TCA performance measure was the participant's qualitative sense of thermal comfort on a 4-

point Likert scale and thermal perception on a 9-point Likert scale. Participant's comfort rating was collected five times, once after each task and once prior to testing. Self-perceived thermal comfort data were associated with their respective condition and used as a descriptive statistic of cold stress. A 2 (condition) X 4 (time/task) RM ANOVA was used to assess significant differences in cold perception and discomfort between conditions. TCA measures were used as predictive metrics for driving behavior using linear regression.

Tympanic and Oral Temperature

Participant's internal body temperature was taken via infrared measurement taken from the tympanic membrane of the ear in degrees Fahrenheit. A 2 (condition) X 4 (time/task) RM ANOVA was used to assess significant differences in cold stress between conditions for each measure. Internal temperature measures were also used as predictive metrics for driving behavior using linear regression.

Skin Temperature

The thermocouple data logger provided mean skin temperature from the abdomen, back, and thigh in degrees Fahrenheit at a sample rate of 0.1 Hz. Temperatures from the four thermocouples were averaged to get an estimated mean skin temperature to quantify cold stress from skin cooling. A two sample t-test was used to assess significant differences in cold stress between conditions. Skin temperature measures were also used as a predictive metric for driving behavior using linear regression.

Driving Simulator

The primary measures of the driving simulator were vehicle behavioral data commonly seen in dangerous driving literature. These data were calculated from a variety of driving simulator measures: vehicle velocity, distance from entity, braking, and lateral lane position. All driving metrics were logged at a sample rate of 5 Hz.

Vehicle velocity was used as a metric to indicate the speed of the participant's vehicle. Velocity was taken directly from the simulator given data and converted into miles per hour. Velocity data were averaged across the whole track and averaged from individual segments of the track for analysis.

Time from car was used as a metric to indicate how long the participant would have to stop at their current velocity before coming into contact with the lead vehicle during the following task. Time from car was calculated by using an average of the simulator recorded distance between the participant's vehicle and the computerized lead vehicle in meters. This distance was then divided by the constant velocity of the lead vehicle in meters/sec to get the time in seconds to cover that distance. The velocity of the lead vehicle was used because this was also the average velocity of the participant during the following task. The first and last 300 meters of the following task were not used in this calculation. This took into account drivers adjusting their initial following distance as well as adjusting their following distance in accordance to the impending stop sign.

Max braking force was used as a metric to indicate what percentage of the car's braking potential was being used (0% = no brake being applied, 100% = the brake pedal being applied as forcefully as possible). Braking force was taken from the simulator given data and the max taken as the participant approached each stop sign.

Starting to brake was used as a metric to indicate how many seconds before a full stop was the brake pedal first applied. The time at which the brake was applied was taken directly from the simulator given data and subtracted from the time at which the participant came to a full stop.

Lateral lane position was used as a metric to indicate how centered the vehicle was in the lane. The lateral distance in meters was taken directly from the simulator given data and analyzes for variability using standard deviation. Lateral standard deviation was calculated across the whole track and averaged from individual segments of the track for analysis.

Results

General

Participants held a valid driver's license for an average of 4.3±4.36 year and estimated they drove 119±160 miles per week. Participants reported on average as having Good to Excellent physical and mental health. No participants reported having joint stiffness, touch sensitivity, attentional disorders, or any disabilities which impaired driving. Participants reported receiving an average of 7.77 hr (*SD*±1.78) of sleep the night before their session and feeling between a 1 and a 3 on the SSS (equating to *wide awake and alert*). Participants reported feeling 4.45 (SD±0.92) for thermal sensation (equating to *neutral*) and 2.11 (SD±0.78) for comfort (equating to *comfortable*) on the TCA prior to the start of the testing session.

The result of an independent samples-t test showed no significant vasoconstriction between conditions from the thigh, *p*>.05. Mean skin temperature (T_{sk}) from an unweighted average of the abdomen, back, and back of thigh was significantly lower in the cold condition, *t*(39)=11.19, *p*<.001 (Figure 7). The results showed a significant decrease in tympanic temperature across the study *F*(3,123)=28.49, *p*<.001, η^2=.410, but not a significant difference between conditions, *F*(1,41)=3.14, *p*=.084 (Figure 8). Similarly, the results showed a significant decrease in lingual temperature across the study *F*(3,123)=10.55, *p*<.001, η^2=.205, but not a significant difference between conditions, *F*(1,41)=0.84, *p*=.363 (Figure 9). It is important to emphasize that after the driving task (task period 1) there was no significant difference in either the tympanic membrane, *t*(42)=1.45, *p*=.155, or the lingual artery *t*(42)=0.79, *p*=.430.

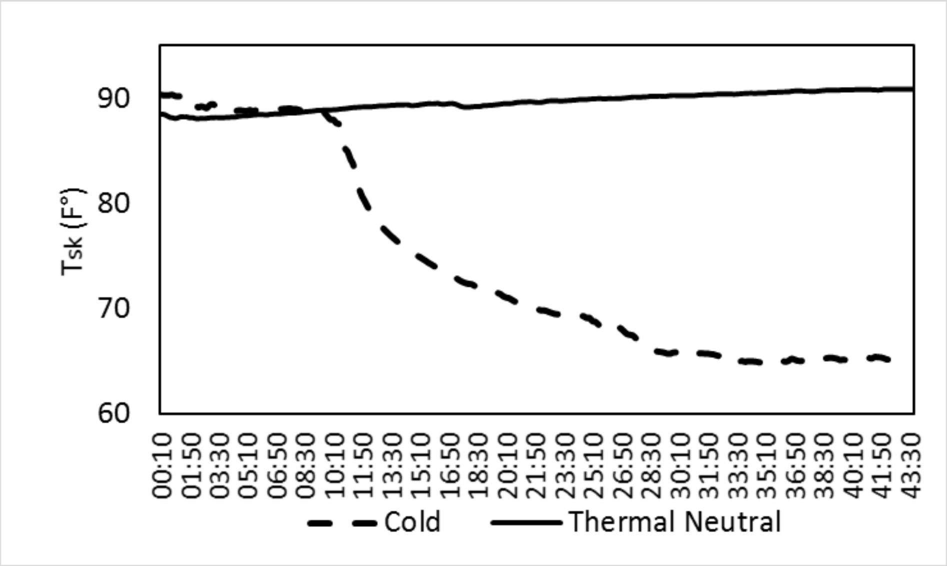

Figure 7. Average skin temperature across the session

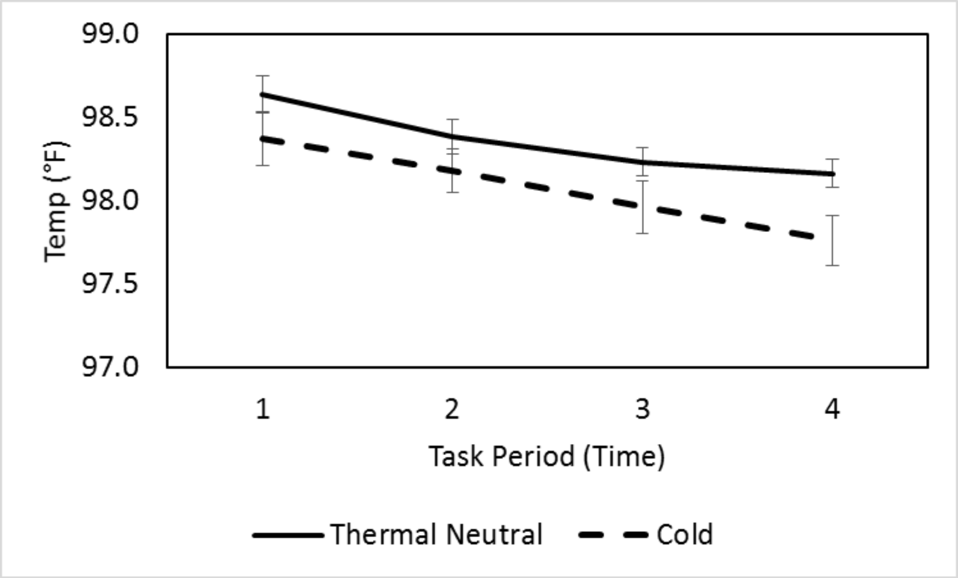

Figure 8. Tympanic temperature across the session. Task period represents the time when the tasks were performed (i.e., 1, measurement taken after first task)

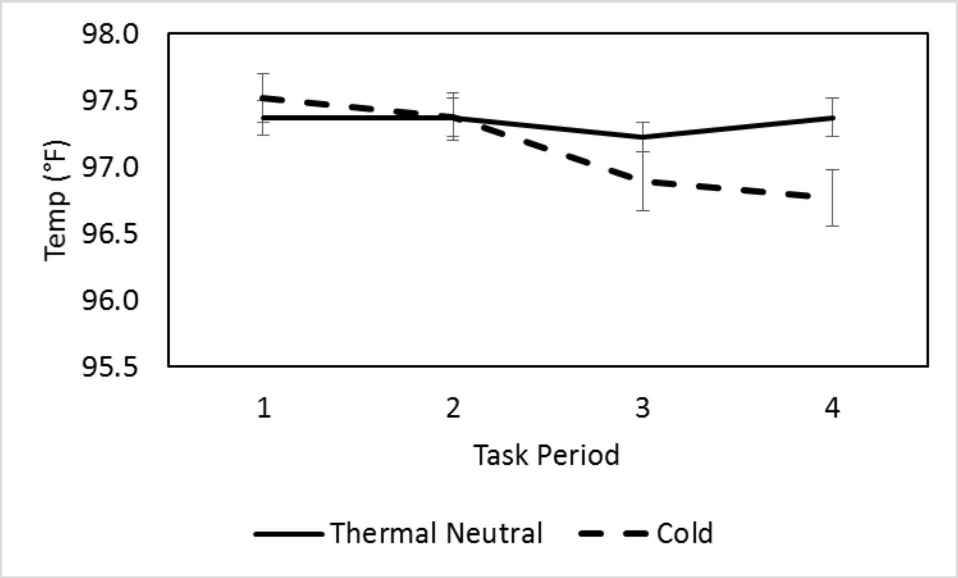

Figure 9. Lingual temperature across the session. Task period represents the time when the tasks were performed (i.e., 1, measurement taken after first task)

Using the TCA cold perception, the results showed a significant difference between condition $F(1,41)=264.68$, $p<.001$, $\eta^2=.866$. When analyzed by task period results showed an increase in subjective feelings of perceived cold over time in the cold condition, $F(3,18)=18.47$, $p<.001$, $\eta^2=.755$; but no change in the thermal neutral condition, $F(1,19)=1.11$, $p=.368$ (Figure 10). Using the TCA comfort, the results showed a significant difference between condition $F(1,41)=92.52$, $p<.001$, $\eta^2=.866$. When analyzed by conditions, results showed no significant change in comfort over time in the cold condition, $F(3,18)=2.20$, $p=.123$; nor in the thermal neutral condition, $F(1,19)=0.38$, $p=.765$ (Figure 11).

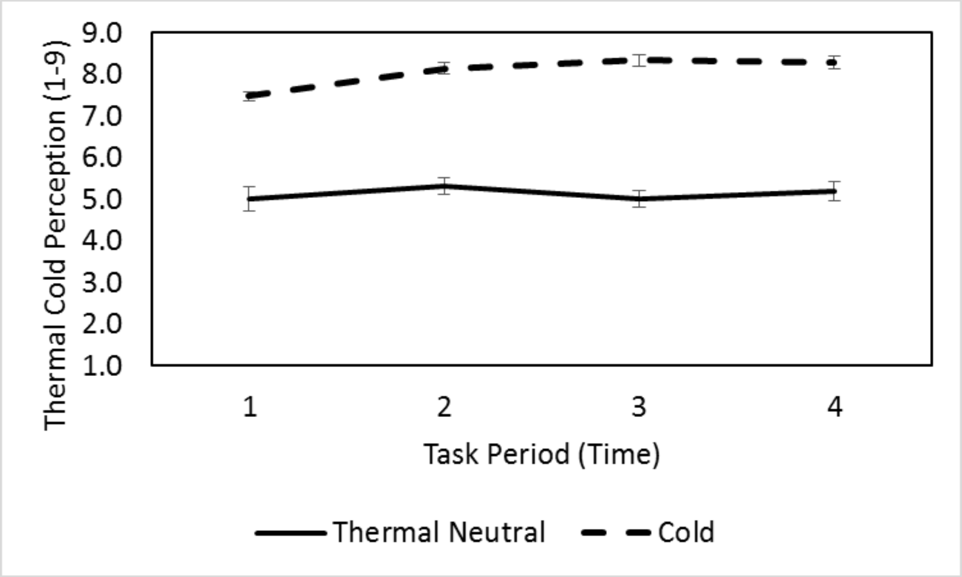

Figure 10. Perceptive cold across the session, 9 being very cold. Task period represents the time when the tasks were performed (i.e., 1, measurement taken after first task)

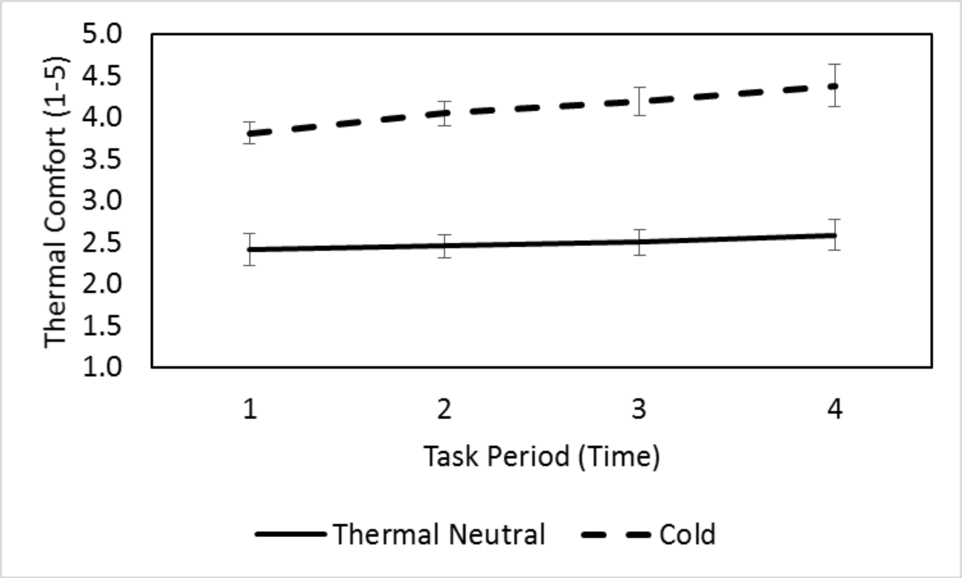

Figure 11. Thermal comfort across the session, 5 being very uncomfortable. Task period represents the time when the tasks were performed (i.e., 1, measurement taken after first task)

Driving Performance

No difference in driving velocity, either averaged from across the whole track or from individual track sections were observed between conditions, *p*>.05. No difference in standard deviation of lateral lane position, either averaged from across the whole track or from individual track sections were observed between conditions, *p*>.05. No difference between conditions was seen for the time to start braking or max braking force for the first two stop signs.

Average following time in seconds was significantly closer (22%) in the cold condition (*M*=2.98 sec) than the thermal neutral condition (*M*=3.80 sec), *t*(42)=2.12, *p*=.040 (Figure 12). Results of a linear regression to predict following distance using the subjective ratings of thermal perception as the predictor were significant β=-.41, *t*(42)=2.96; R^2=.17, *F*(1,42)=8.77, *p*=.005) (Figure 13); however, the subjective ratings of thermal comfort were not a predictor of following distance, *p*>.05. During the following task, the average amount of lateral movement in the lane was no different between conditions, but was predicted negatively by subjective ratings of cold perception *β*=-.347, R^2=.12, *F*(1,42)=5.75, *p*=.021 (figure 14); again subjective ratings of thermal comfort were not a predictor, *p*>.05.

However, drivers delayed starting to brake by over two seconds at the third stop sign in the cold condition (*M*=9.19 sec) compared to the thermal neutral condition (*M*=11.54 sec), *t*(42)=2.22, *p*=.031 (Figure 15). As a result, the amount of max braking force used at the third intersection was considerably greater and approached significance in the cold condition (*M*=42% of *max*) as compared the thermal neutral condition (*M*=35% of *max*), *t*(42)=1.98, *p*=.053. Subjective ratings of thermal perception significantly predicted delayed braking behavior only at the third stop sign β=-.363, *t*(42)=2.52; R^2=.13, *F*(1,42)=6.37, *p*=.015 (Figure 16); while the subjective ratings of thermal comfort did not, *p*>.05.

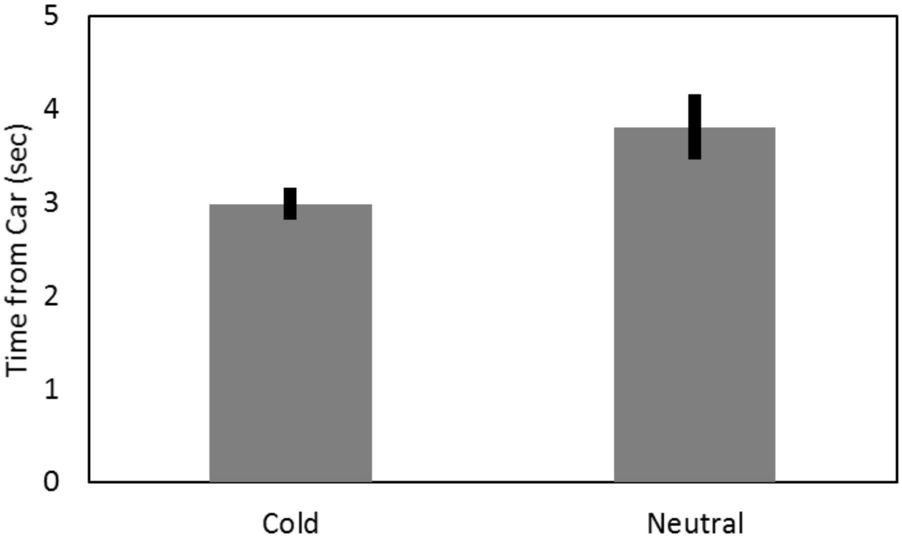

Figure 12. Following distance in seconds during the driving following task

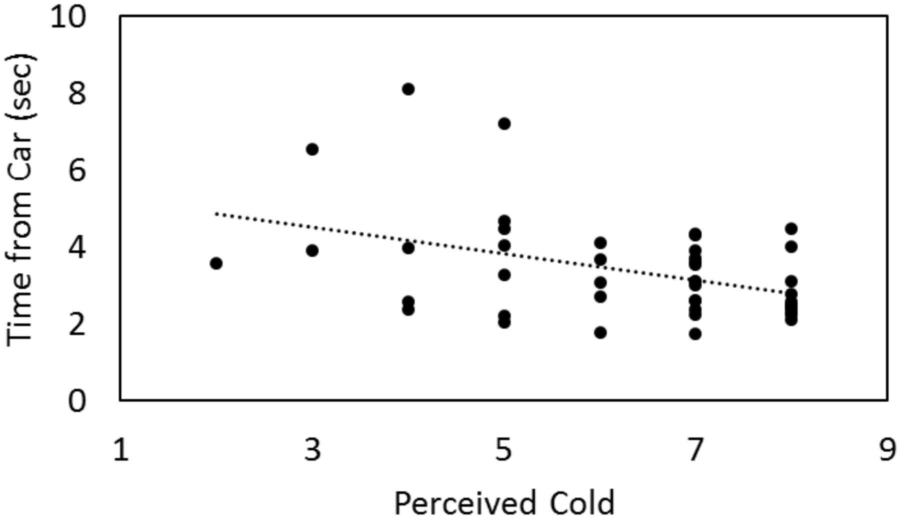

Figure 13. Following distance in seconds predicted by perceived cold

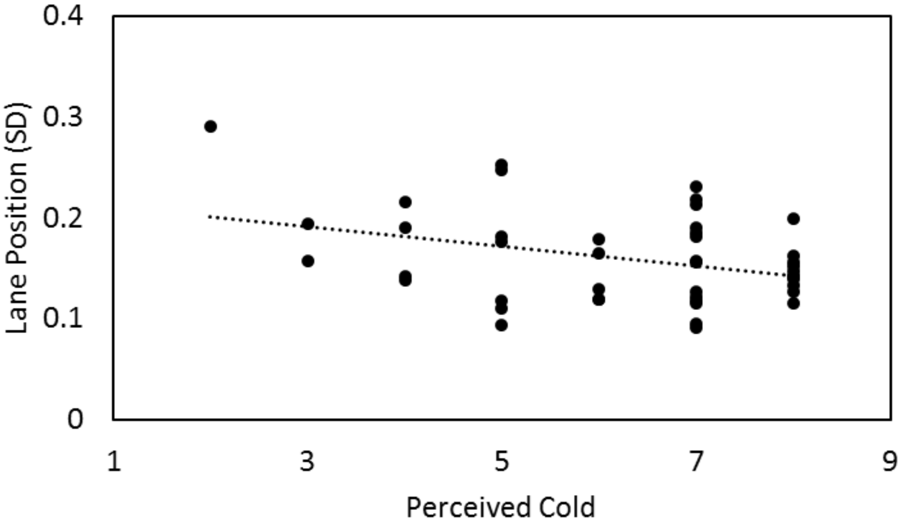

Figure 14. Lane position standard deviation predicted by perceived cold

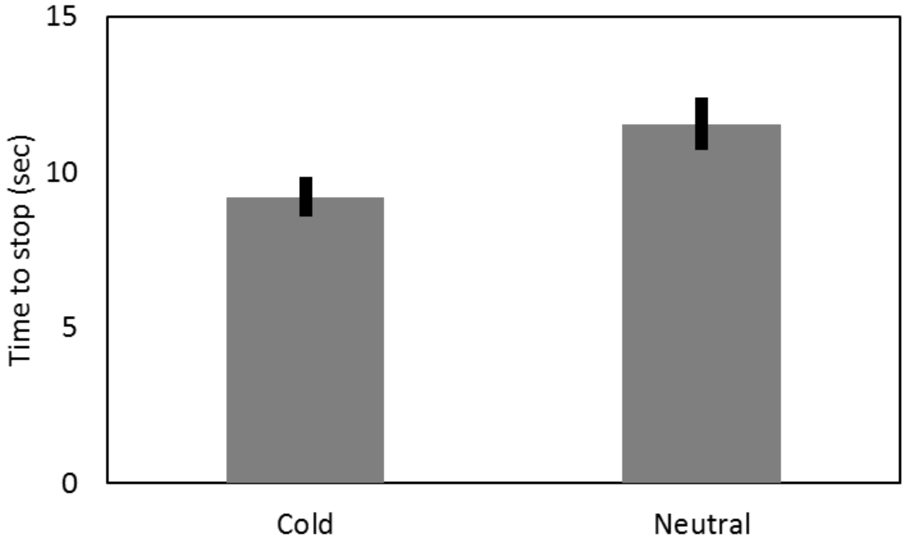

Figure 15. The time from the first application of the brake to coming to a full stop at the third stop sign

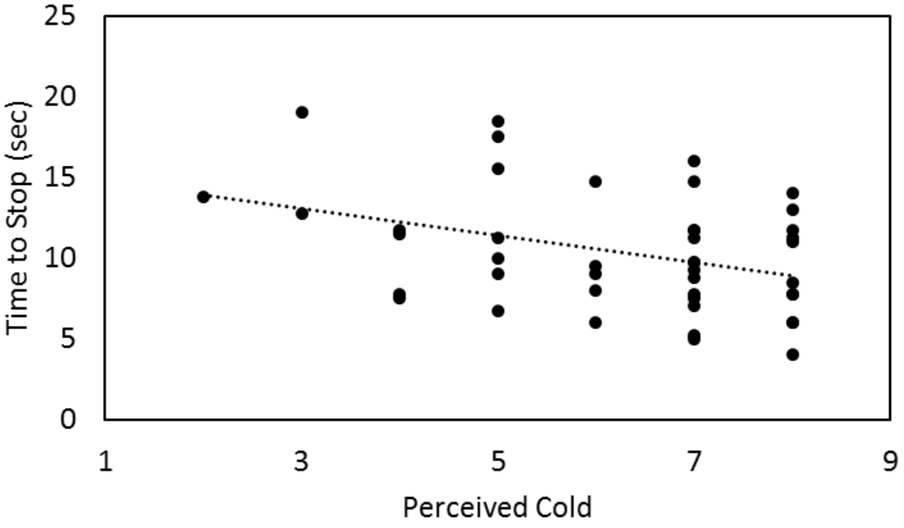

Figure 16. The time from the first application of the brake to coming to a full stop predicted by perceived cold

Additional Measures

Using the computerized psychomotor vigilance task as a control measure, no significant difference in reaction time between the cold and thermal neutral conditions was observed, $p>.05$. Additionally, no significant difference in response lapses at 500 or 1000 ms were observed between conditions, $p>.05$. Using four trials of the Minnesota Manual Dexterity placing task to test for physical decrements as a control measure, no significant difference in task completion time was observed, $p>.05$.

Discussion

The results of this study found that exposure to mild cold stress can impact driving behavior. Cold condition participants chose to follow a lead car closer and stop quicker after following a lead car. By controlling for reaction time, attention and physical dexterity, the findings seem to indicate that differences between conditions are largely due to behavioral choices as opposed to physiological curtailment. In addition, these differences only appeared after a psychological stressor (e.g., following another vehicle), suggesting aggression may play a role in explaining this effect.

Hypotheses

As a manipulation check and explanatory variable, participants in the Cold condition reported more thermal discomfort and an increased perception of cold than the Thermal Neutral condition. This occurred alongside a decrease in mean skin temperature, as was anticipated by the first hypothesis. Results of a psychomotor vigilance task as a control measure for overt cognitive decrement showed the Cold condition and Thermal Neutral condition did not vary in performance, supporting the second hypothesis. Likewise, results of the dexterity task as a control measure for overt physical decrement showed the Cold condition and Thermal Neutral condition did not vary in performance, supporting the third hypothesis. Lastly, lateral lane position variability and velocity were not different between conditions during the driving task. However in partial support of the fourth hypothesis, following behavior and braking behavior after following were significantly different.

General Discussion

Results showed that the cold stressor was an effective methodology for inducing non-hypothermic cold stress. Temperature sensors located on the skin showed a significant decrease in skin temperature over time, yet core temperature was not different between the Cold and Thermal Neutral group. Those in the cold stressor condition also reported feeling more cold and uncomfortable on a subjective scale. However, the thermal stress in the study is considered weak. Such thermal stress was not able to bring about significant physiological reactions in the cold condition, meaning psychomotor vigilance was not affected. Some studies have shown that cold environments hinder physical movement, but the weak stressor was not found to affect dexterity either (Ducharme et al., 1999; Heus et al., 1995). A weak stressor would be expected in the real world where temperatures are not often extreme. Drivers would feel cold because of the thermally stressful environment, but insulated clothing would ward off changes in core temperature and profound physiological reactions.

The current simulated driving findings indicate that short exposure to mild cold stress can negatively impact driving behavior. Unexpectedly, changes in diving behavior occurred primarily during a following task and not in the driving metrics most common seen in dangerous driving literature. Dangerous diving literature suggests stress has a profound impact on lateral lane position and vehicle velocity, most commonly attributed to lapses in attention (Matthews, Sparkes, & Bygrave, 1996; Morris, Pilcher, & Switzer III, 2015; Vitabile, De Paola, & Sorbello, 2011). No difference in lateral lane position or velocity was seen in the current study, which coincides with the lack of attention lapses measured with the psychomotor vigilance task. Cold stress impacted subjective ratings - however, it had no overt physiological or psychophysiological impact - as indicated by measures of vasoconstriction, attention lapse, reaction time, and dexterity. As such, the root cause for driving behavior seems to be largely psychological, stemming from perceived cold. If driving differences during cold stress do stem from personal choice as opposed to psychophysiological limitations, it seems unlikely dangerous driving detection technology, which relies on traditional data from lane variability, would be effective in detecting dangerously cold drivers.

One key component of the driving task was the presence of another vehicle. The lead vehicle during the following task was designed to drive consistently 10mph under the prescribed speed limit of 55mph, and acted as a psychological stressor. Research has shown that driving is a psychological stressor, largely moderated by driver aggression and interactions with other vehicles, specifically during passing or unsuccessfully passing (Gulian, Matthews, Glendon, Davies, & Debney, 1989). Previously, researchers have also shown that feelings of stress while driving predicted risk taking behavior and chance of at-fault accidents (Legree, Heffner, Psotka, Martin, & Medsker, 2003). Moreover, increased stress behind the wheel has been linked to aggression behind the wheel (Hennessy & Wiesenthal, 1999). Researchers have found that uncomfortably cold temperatures also increase negative affect, hostile cognition, and aggressive behavior (Anderson, 1989). Many of these negative effects occur due to cooled skin temperature during non-hypothermic periods of short cold exposure. Non-hypothermic cooled skin conditions are similar to the exposure drivers would feel in a car cabin before the heating system could moderate cold cabin temperature.

Only after exposure to both the cold stressor and the psychological stressor of having to following another vehicle did the participants change driving behavior. Changes in driving behavior included following the lead vehicle closer, braking with more force, and delaying the application of the brake; behaviors that have been associated with aggressive driving. Aggression while driving can manifest itself in multiple ways, with tailgating and braking being two of the most common behaviors (Habtemichael & de Picado Santos, 2014; Harris et al., 2014). Interestingly, changes in behavior occurred even when the following portion of the task lasted only two minutes. These changes in driving behavior were predicted by subjective feelings of cold, but not subjective feelings of discomfort. This suggests a role of driver perception when reacting to short-term environmental stressors. In this case, the drivers may not have felt discomforted by the cold environment but they still reacted negatively to the combined stressor of the lead vehicle and the cold stress. These findings are the first to suggest cold drivers may demonstrate more aggressive driving behavior.

The National Highway Traffic Safety Administration found that aggressive driving behavior was perceived as the top cause of vehicle crashes (Preusser Research Group, 1998). Aggressive driving may be in part due to stressful driving conditions exacerbated by uncomfortable vehicle temperatures (Anderson, Deuser, & DeNeve, 1995). According to this theory, environmental temperatures act primarily as a priming agent for aggression, but require an additional psychological stress before aggressive driving behavior is shown (Rule, Taylor, & Dobbs, 1987). In the current study, following a lead vehicle that is going slower than the speed limit could have been the catalyst for aggressive driving behavior when combined with the cold stressor. In the case of the present stop sign findings, this would help explain why aggressive braking behavior would only occur in the cold condition and only after participants had to follow another vehicle driving below the speed limit. Similarly, there was no difference in driving velocity between conditions, though cold condition participants chose to follow closer during the following task.

Previous meta-analytic findings in the field of attentional research have also suggested the impact of cold stress on attention is significant in task performance (Pilcher et al., 2002). The observed reduction in lateral lane movement during following as predicted by subjective ratings of cold perception suggests cold drivers may be more fixated on the lead car during the following task. This fixation may be attributed to the cold stress manipulation and cold-aggression mechanism, as negative affect seems to promote a self-focused attention and egocentric goal orientation (Mor & Winquist, 2002) which may contribute to differences in following behavior.

Limitations and Future Research

Though the design was carefully considered, the current study is not without limitations. One limitation is the sample population, southern college students are not necessarily a representative age group for the study. Research has suggested that age is a moderating variable in both driving and thermoregulatory response, and may have impacted the findings

(Parsons, 2002; Royal, 2003). Future research can look to include a broader age range population. Another limitation is the geographic location of the sample population, as personal experience can impact subject feeling of cold discomfort (Parsons, 2002). The population consisted of residents of a warm southern state who may feel more uncomfortable at mild temperatures, impacting the generalizability of the subjective data used in the study. Though the effect of geographic location is expected to be negligible, literature is unclear as to what effect the demographic could have in a cold driving scenario and should be explored

Another threat to external validity was the use of a simulated cold vehicle. In the interest of being able to accurately measure vehicle behavioral metrics, the high fidelity driving simulator was a critical tool. The simulator allowed the driver to perform the tasks safety without the threat of injury due to mistakes. However, a driving simulator cannot perfectly mimic a vehicle in the real world. Driving simulation research that takes place in a climate chamber could be explored in future research. The study also used icepacks to cool participants instead of using a room sized climate chamber. The cold stress methodology used in the study was effective, but was not capable of cooling all parts of the body directly, as may be the case in a real cold environment. Though a climate chamber was not available at the time of data collection and are often expensive to operate, grant funding could make this a viable option for future research.

It is also worth noting that though the study suggests the role of aggression in driving behavior during cold stress, the study did not directly measure aggression. The observed driving behavior was similar to that found in aggressive driving literature, but aggression itself was not measured using a subjective aggression scale. The cold aggression paradigm was a serendipitous finding that has not been seen in driving literature and was therefore unanticipated. In lieu of this finding, future research on the subject should incorporate a subjective aggression index. Directly measuring aggression would allow for median-split and correlational analysis that focuses on the relationship between aggressive feelings and driving behavior.

Conclusion

Although the effect of cold stress has been documented in a number of settings, the effects of cold stress on driving behavior is overdue in accident analysis. The present stressor was mild and as such did not elicit many of the physiological changes that often curtail task performance in more extreme thermal environments. As a result, the unexpected findings of this study suggest the role of cold environments in following behavior. Following behavior may be partially explained through an aggression paradigm when an additional psychological stressor is present. Close following behavior remains a leading cause of vehicle accidents (Muhrer & Vollrath, 2010) and one that has not been considered with respect to environmental temperature. General aggressive behavior behind the wheel increases the likelihood of collision involvement, though its cause is not often considered (Legree et al., 2003; Preusser Research Group, 1998). As such, the current study provides a new perspective on an important area of research. The present findings are some of the first to suggest a relationship between perceived thermal stress and driving behavior and suggest that cabin temperature could contribute to some cases of dangerous and perhaps aggressive following behavior.

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Appendices

[1]

General Information

General Information

Participant Number:____	DoB:	Sex: M [ ] F [ ]
Name:	Email:	Phone Number:

Student Year at Clemson: Fr. [ ] So. [ ] Jr. [ ] Sr. [ ] Grad. [ ]

General Ability

1. Are you proficient at reading and speaking English: Y [ ] N [ ]
2. Do you possess a valid Driver's License: Y [ ] N [ ]
   If yes, how long have you held a license to drive: years
   If yes, approximately how many miles do you drive per week:

General Health

3. How would you rate your overall physical health:
   Excellent [ ] Good [ ] Average [ ] Fair [ ] Poor [ ]
4. How would you rate your overall Mental health:
   Excellent [ ] Good [ ] Average [ ] Fair [ ] Poor [ ]
5. Do you take any medications regularly: Y [ ] N [ ]
   If yes, please list the medication and reason for taking:
6. If you are female, are you pregnant or thinking you may be pregnant: Y [ ] N [ ]
7. Have you been diagnosed with or suffer from any of the following:
   Overt sensitivity to touch in your hands or feet: Y [ ] N [ ]
   Experience numbness or tingling in your hands or feet: Y [ ] N [ ]
   Stiffness of joints effecting your ability to move : Y [ ] N [ ]
   Hypothalamic disorders: Y [ ] N [ ]

Attentional disorders: Y [ ] N [ ]

8. Do you have any disability that would impact your ability to drive a vehicle: Y [ ] N [ ]
   If yes, what:

9. Do you have a medically implanted pacemaker: Y [ ] N [ ]

10. Do you have normal hearing: Y [ ] N [ ]

11. Do you have normal vision (with use of contacts or glasses if necessary): Y [ ] N [ ]

12. Do you have normal feeling in your hands and feet: Y [ ] N [ ]

13. Do you have normal feeling of temperature: Y [ ] N [ ]

14. Have you ever experienced sickness (nausea, headaches, sweating) from a virtual 3D simulator: Y [ ] N [ ]

15. Do you possess any mental or physical health issues that have not been mentioned that you are aware of: Y [ ] N [ ]
   Is yes, please explain:

Sleep Health

16. Would you consider yourself a "normal sleeper" for someone your age: Y [ ] N [ ]

17. How would you rate your overall sleep habits:
   Excellent [ ] Good [ ] Average [ ] Fair [ ] Poor [ ]

18. Do you get most of your sleep during the night: Y [ ] N [ ]

19. Have you been diagnosed with a sleeping disorder: Y [ ] N [ ]
   If yes, please describe and indicate how long you have had the problem:

20. On average, how long do you usually sleep at night: hours and minutes

Consumption

21. On average, how many (cups, cans, bottles) per day do you drink of the following:
   Caffeinated Coffee: cups per day

Decaffeinated Coffee:	cups per day
Tea:	cups/bottles per day
Carbonated soft drink with caffeine:	cans/bottles per day
Other:	cans/cups/bottles per day

22. Do you drink any alcohol: Y [ ] N [ ]
    If yes, do you feel you are a normal drinker for someone your age: Y [ ] N [ ]
    Would your friends or relatives think you are a normal drinker: Y [ ] N [ ]

23. Do you use any tobacco products: Y [ ] N [ ]
    If yes, what, and how much per day:

24. Would your friends or relatives think you have a problem with drugs use of any kind:
    Y [ ] N [ ]

[2]

Participant Time Slots

Participant Number:____

This study will take place over one session. You are required to arrive at the lab five minutes early and to be wearing athletic outerwear (gym shorts, low cut socks, and cotton-t shirt, gym shoes) with underwear. On the day of testing, please refrain from consuming any energy products, caffeine or alcohol. On the night before your scheduled testing day you should attempt to get a full eight hours of sleep, and should wake up at least two hours prior to your scheduled time.

***The exact scheduled date will be selected later, depending on availability.**

Please check all possible days and time periods you would usually be available. Participation takes approximately 1 hours. You will only be selected to come in one of the days.*

Monday	11:00AM – 12:00PM	[ ]
Monday	1:30PM – 2:30PM	[ ]
Monday	4:00PM – 5:00PM	[ ]
Tuesday	11:00AM – 12:00PM	[ ]
Tuesday	1:30PM – 2:30PM	[ ]
Tuesday	4:00PM – 5:00PM	[ ]
Wednesday	11:00AM – 12:00PM	[ ]
Wednesday	1:30PM – 2:30PM	[ ]
Wednesday	4:00PM – 5:00PM	[ ]
Thursday	11:00AM – 12:00PM	[ ]
Thursday	1:30PM – 2:30PM	[ ]
Thursday	4:00PM – 5:00PM	[ ]
Friday	11:00AM – 12:00PM	[ ]
Friday	1:30PM – 2:30PM	[ ]
Friday	4:00PM – 5:00PM	[ ]
Saturday	11:00AM – 12:00PM	[ ]
Saturday	1:30PM – 2:30PM	[ ]
Saturday	4:00PM – 5:00PM	[ ]
Sunday	11:00AM – 12:00PM	[ ]
Sunday	1:30PM – 2:30PM	[ ]
Sunday	4:00PM – 5:00PM	[ ]

[3]

Pre-Testing Information

Participant Number: Date:

Biometrics

Weight: lbs Height: inches Approx. Body Fat: %

Tympanic Temperature: °F Lingual Temperature: °F

Skin Temperature Location: 1: °F 2: °F 3: °F 4: °F

Sleep Information

1. Estimate the time in minutes that you napped yesterday: minutes
2. Did you use a sleep aid to fall asleep last night: Yes [ ] No [ ]
   If yes, what kind of sleep aid:
   If yes, how many times per week do you use a sleep aid:
3. Estimate the time you went to bed with the intention of sleeping last night:
4. Estimate your total time in bed last night before you fell asleep:
   hours and minutes
5. Estimate your total time asleep last night:
   hours and minutes
6. Estimate the total number of awakenings that you experienced during the night:
7. Estimate the time you got out of bed this morning:
8. How would you rate the quality of last night's sleep:
   Excellent [ ] Good [ ] Average [ ] Fair [ ] Poor [ ]

Initial Qualitative Information

9. Stanford Sleepiness Scale Rating [1-7]:
10. Thermal Comfort Assessment Rating [1-9]: [1-4]: Shivering**:** Yes [ ] No [ ]

11. Simulator Sickness Symptoms Rating:

Nausea Score Sum: (1,6,7,8,12,13,14,15,16):

Oculo-Motor Score Sum: (2,3,4,5,9,10,11) :

Overall Rating [0-48]:

[4]

Session Scores

Participant Number: Date:

Minnesota MD – Placing Task

Condition: Neutral [ ] Cold [ ] Time:

PVT – Reaction Time

Condition: Neutral [ ] Cold [ ] Time: Lapses:

PVT – Attention Lapse

Condition: Neutral [ ] Cold [ ] Number of Lapses:

SSS and SSQ

Condition: Neutral [ ] Cold [ ] SSS Score [1-7]: *Attach SSQ*

Condition: Neutral [ ] Cold [ ] SSS Score [1-7]:

TCA and Temperature

Condition: Neutral [ ] Cold [ ] Score [1-9]: Score [1-4]:

Location: Simulator [ ] Additional Tasks [ ] Ear Temp: °F Oral Temp: °F

Condition: Neutral [ ] Cold [ ] Score [1-9]: Score [1-4]:

Location: Simulator [ ] Additional Tasks [ ] Ear Temp: °F Oral Temp: °F

[5]

Stanford Sleepiness Scale (SSS)

An Introspective Measure of Sleepiness

To be administered after each driving task

How I feel… (**circle one**)

1 Feeling active, vital, alert, or wide awake

2 Functioning at high levels, but not at peak; able to concentrate

3 Awake, but relaxed; responsive but not fully alert

4 Somewhat foggy, let down

5 Foggy; losing interest in remaining awake; slowed down

6 Sleepy, woozy, fighting sleep; prefer to lie down

7 No longer fighting sleep, sleep onset soon; having dream-like thoughts

[6]

Issues and Unexpected Occurrences During Testing

Participant Number: Date:

Event

Condition: Neutral [   ]   Cold [   ]

Task: Participant [   ]   Core/Skin Temp [   ]   PVT [   ]   MMDT [   ]   Atten. [   ]   Driving [   ]   Other [   ]

Description of Issue:

Condition: Neutral [   ]   Cold [   ]

Task: Participant [   ]   Core/Skin Temp [   ]   PVT [   ]   MMDT [   ]   Atten. [   ]   Driving [   ]   Other [   ]

Description of Issue:

Condition: Neutral [   ]   Cold [   ]

Task: Participant [   ]   Core/Skin Temp [   ]   PVT [   ]   MMDT [   ]   Atten. [   ]   Driving [   ]   Other [   ]

Description of Issue:

Verbal Instructions Given to Participant during Testing Sessions

[7]

Summary

We will begin by taking some body measurements, and then you will be set up with a skin temperature monitoring system. Following this, we will begin the testing procedure. You will be trained on and tested using a reaction time device, a manual dexterity task, an attention task, and a driving simulator. To record your performance and condition you will be asked questions pertaining to your sleepiness and comfort, and have your core temperature taken at your ear and mouth. Participation should take approximately 2 hours. Do you have any questions?

Driving Simulator

The object of this task is to see how well you can drive around a simulated track. The track consists of a single circuit, and the task will be finished once you complete the full circuit. The road is made up of a variety of turns, hills and straight segments, and you should try to remain as centered in the lane as possible. While on the track, please observe all traffic laws and signage, including the roads 55 mile per hour speed limit. The driving simulator operates identically to a traditional automatic transmission car. Accelerator pedal, brake pedal, and steering wheel are fully functioning and may provide force feedback. The vehicle is on a two axis moving platform, and movement may result in feelings of simulator sickness. If you are feeling the signs of simulator sickness as described in the simulator sickness questionnaire, please inform the researcher immediately. You are encouraged to drive as you normally would on dry road conditions. The Task will take approximately 15 minutes. Do you have any questions?

Minnesota Manual Dexterity Task

The object of this test is to see how fast you can put the disks into the holes of the board using only one hand. You will want to use your dominant hand. You must begin on your RIGHT. Pick up the bottom disk and insert the disk into the top hole of the board. Now, you must pick up the next disk in the column on the right, and so on. You will move from right to left on this test. Once you complete one column, repeat the previous sequence in the second column until you have filled the entire board. You may hold the board with your free hand if you wish to do so. Do you have any questions?

PVT Attention Lapse

The object of this test is to see how fast you can press the response button once prompted. Hold the device in both hands, with the thumb of your dominant hand on one of the two square black buttons. At random intervals, the device will start a timer and display the time in green text. Once you see the text, immediately press the response button. Once the button is successfully pressed, the timer will stop and the green text will disappear leaving a black screen for a brief period. The process will continue for several trials. If you press the button before the timer starts, the device will display an FS, for false start, and will pause briefly before starting a new trial. The Task will take approximately 10 minutes. Do you have any questions?

PVT Reaction Time

The object of this test is to see how fast you can press the response button once prompted. Hold the device in both hands, with the thumb of your dominant hand on one of the two square black buttons. At random intervals, the device will start a timer and display the time in green text. Once you see the text, immediately press the response button. Once the button is successfully pressed, the timer will stop and the green text will disappear leaving a black screen for a brief period. The process will continue for several trials. If you press the button before the timer starts, the device will display an FS, for false start, and will pause briefly before starting a new trial. The Task will take approximately 5 minutes. Do you have any questions?

Stanford Sleepiness Scale

Please answer the following question pertaining to your present feeling of sleepiness. The Scale is as follows: Feeling active, vital, alert, or wide awake; Functioning at high levels, but not at peak, able to concentrate; Awake, but relaxed, responsive but not fully alert; Somewhat foggy, let down; Foggy, losing interest in remaining awake, slowed down; Sleepy, woozy, fighting sleep, prefer to lie down; No longer fighting sleep, sleep onset soon, having dream-like thoughts. Do you have any questions?

Simulator Sickness Questionnaire

Please answer the following 16 questions pertaining to your present feeling of comfort regarding the use of the simulator. The scale is as follows: None; Slightly; Moderate; Severe. Do you have any questions?

Thermal Comfort Assessment

Please answer the following 2 questions pertaining to your present feeling of comfort regarding temperature. The scale of the first question is as follows: Very Hot; Hot; Warm; Slightly Warm; Neutral; Slightly Cool; Cool; Cold; Very Cold. The scale of the second question is as follows: Very Comfortable; Comfortable; Neutral; Uncomfortable; Very Uncomfortable. Do you have any questions?

[8]

Thermal Comfort Assessment (TCA)

An Introspective Measure of Thermal Comfort – Based on ISO 10551

To be administered after each driving task

How I feel… (**circle one**)

8 Very Hot
9 Hot
10 Warm
11 Slightly Warm
12 Neutral
13 Slightly Cool
14 Cool
15 Cold
16 Very Cold

How I feel… (**circle one**)

1 Very Comfortable
2 Comfortable
3 Neutral
4 Unconformable
5 Very Uncomfortable

Visible Shivering**:** Yes [ ] No [ ]

Visible Sweating**:** Yes [ ] No [ ]

[9]

Simulator Sickness Questionnaire (SSQ)

Participant Number: Date:

An Introspective Measure of Simulator Comfort

To be administered after each driving task

Condition: Neutral [ ] Cold1 [ ] Cold2 [ ]

How I feel… (**circle one**)

1	General discomfort	None	Slight	Moderate	Severe
2	Fatigue	None	Slight	Moderate	Severe
3	Headache	None	Slight	Moderate	Severe
4	Eye strain	None	Slight	Moderate	Severe
5	Difficulty focusing	None	Slight	Moderate	Severe
6	Salivation increasing	None	Slight	Moderate	Severe
7	Sweating	None	Slight	Moderate	Severe
8	Nausea	None	Slight	Moderate	Severe
9	Difficulty concentrating	None	Slight	Moderate	Severe
10	« Fullness of the Head »	None	Slight	Moderate	Severe
11	Blurred vision	None	Slight	Moderate	Severe
12	Dizziness with eyes open	None	Slight	Moderate	Severe
13	Dizziness with eyes closed	None	Slight	Moderate	Severe
14	*Vertigo	None	Slight	Moderate	Severe
15	**Stomach awareness	None	Slight	Moderate	Severe
16	Burping	None	Slight	Moderate	Severe